Universal Properties of Modulated Antiferromagnetic Systems

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Magnetism and superconductivity/superfluidity are physical phenomena whose foundations are rooted in quantum mechanics and whose technological applications do not cease to surprise mankind. A fundamental open question in systems where these phenomena may co-exist is the relation between (confined) magnetic and (deconfined) superfluid/superconducting orders. For example, spin fluctuations are thought to be one of the possible mechanisms of the high temperature superconductivity in the cuprates. In this regard, neutron-scattering experimentalists have argued that their techniques could definitely shed some light on the competition and conjectured superconducting *glue*. Recently, we argued that recent inelastic neutron-scattering measurements performed in cuprate superconductors simply indicate that they are prominent representatives of a class of magnetic materials, we christened *modulated antiferromagnetic systems* (MAS). The class, however, is not exclusive to these superconductors. Indeed, we have predicted many materials that should belong to this class, several of them being insulators.

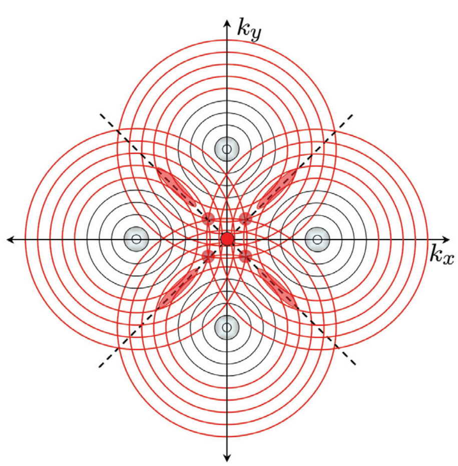

Fig. 1. ***Illustration of the emergence of universal properties in MAS. The plane (k_x, k_y) represents momentum space, while the axis perpendicular to it represents the energy of excitations. The figure schematically shows how cones (whose increasing radius relates to increasing energy) centered at the Goldstone modes, or incommensurate points, etc.(indicated by dark circles), give rise to maxima in intensity because of a simple constructive interference as we move along the direction of increasing energy. The resonance peak, that lies at the center, and the twist in intensity after the resonance energy (depicted as blurred circles along the diagonals) represent some of these universal properties. Therefore, these universal signatures are simply the result of a topological characteristic of the spectrum and, thus, are independent of the microscopic details of the MAS.***

Five years ago [1], we claimed that the *resonance* peak observed in several high-T_c superconductors has a magnetic origin and that it is a natural and universal consequence of the low energy incommensurate magnetic fluctuations which appear close to the two-dimensional $\mathbf{Q} = (\pi, \pi)$ antiferromagnetic wavevector. Moreover, we stated that any system with a magnetic dispersion relation exhibiting minima at wavevectors $\mathbf{q}^{\pm} = \mathbf{Q} \pm \delta\pi\hat{\mathbf{k}}$, where $\hat{\mathbf{k}}$ is a unit vector and $\delta \ll 1$, should exhibit a peak in the magnetic structure factor $S(\mathbf{q}, \omega)$ at $\mathbf{q} = \mathbf{Q}$ and $\omega = E_r$. The peak results from the superposition of the two low-energy magnetic branches that emerge from $\mathbf{q}^{\pm}$ and converge at the saddle point at $\mathbf{q} = \mathbf{Q}$ (see Fig. 1). The actual value of the energy E_r depends on the slope of the low-energy branches (spin velocity). Based on this observation, we predicted [1] that a similar peak should be observed in insulating systems that exhibit modulated antiferromagnetic order like $La_{1.69}Sr_{0.31}NiO_4$. This prediction was later confirmed by Bourges, et al. [2]. Succesive measurements of different high-T_c compounds are confirming the idea that a universal magnetic spectrum plus a spin gap can explain various observations in the cuprates [1, 3].

Despite our theory being repeatedly confirmed by neutron scattering experiments, last findings were interpreted as evidence against our predictions [5]. Two independent groups [5, 6] observed that highest intensity high-energy magnetic excitations (above the resonance energy) are rotated 45° from the incommensurate wavevectors. This behaviour was observed in two different compounds $La_{1.875}Ba_{0.125}CuO_4$ [5] and $Yba_2Cu_3O_{6.6}$ [6]. While the first compound exhibits long-range charge and spin ordering [4], the latter only exhibits short range dynamical correlations. We have recently shown that our theory not only contains the observed twist in the high-energy excitations but also predicts many other insulating systems depicting the same *saddle-point* effect. Since this feature is universal, its observation is not sufficient to discriminate between competing theories that include the incommensurate magnetic correlations (such as 2-leg ladder, etc.). Apart from explaining the twist, we also predicted additional universal signatures that should be observable both in the cuprates as well as in the magnetic insulators that exhibit incommensurate magnetic ordering.

The universal behaviors of MAS are a simple consequence of a few qualitative aspects of the magnetic dispersion relation. This is illustrated by Fig. 1 which shows the qualitative aspects that emerge from the intersection of four cones centered on each incommensurate wavevector (the four low-energy modes result from averaging over the horizontal and vertical orientations). It is important to note that an isotropic conical shape of the low-energy dispersion is only expected for the insulating materials. This is no longer true for metals in which the magnetic branches that move away from the commensurate point **Q** can be overdamped by the particle-hole continuum of excitations. This effect, as well as the presence of a spin gap or a possible anisotropy of the conical shape, *do not* change the following qualitative properties: a) The four cones converge at a saddle point at **q** = **Q** and the corresponding increase in the spectral weight leads to the observed *resonance* peak [1]; b) For higher energies, the intersections between pairs of adjacent cones leads to four points with higher intensity that are rotated 45° relative to the incommensurate wavevectors; c) A similar twist should be observed for energies $0.7E_r \le hw \le 0.9\ E_r$. While a) and b) are experimental facts, c) is a new prediction that requires experimental confirmation. All these universal signatures are merely consequences of the topological characteristics of the spectrum of magnetic excitations (see Fig. 2).

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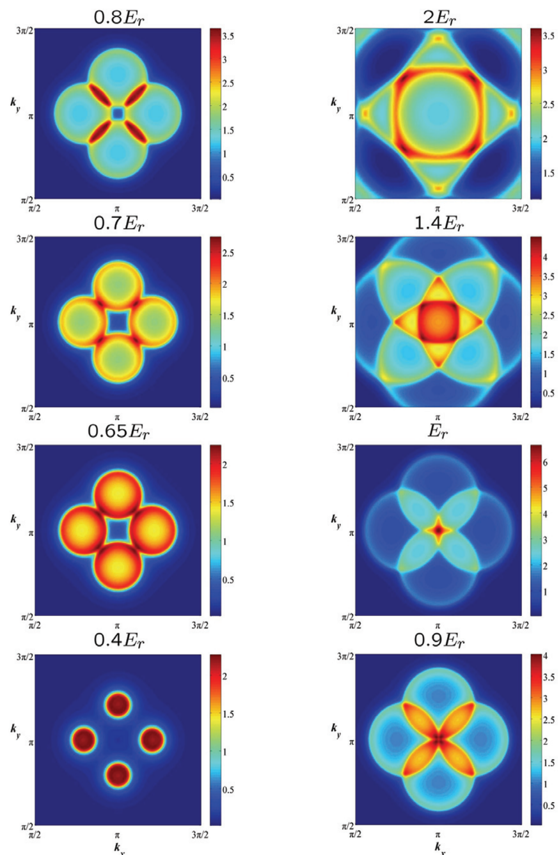

Fig. 2.
Constant energy contour plots of the magnetic structure factor S(k, ω) (intensity) centered around k = Q = (π, π). For this particular example, we have used the Schwinger-boson mean-field result of Ref. [1]. Notice the way the maxima in intensity evolves as ω increases. Indeed, some of these universal features have been experimentally observed in the cuprates, while others represent our predictions. For example, there ought to be a twist in the location of the maxima for energies close but smaller than the resonance energy, which should be observable if higher experimental resolution were available.

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